Simulations of the Maine Coastal Current
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Abstract
The Maine Coastal Current (MCC) is initiated in the eastern Gulf of Maine, travels westward along the northern and western Gulf margins, and exits along the eastern tip of Cape Cod toward the Great South Channel. In previous work seasonal influences on this coastal current during late winter and spring were described. The purpose here is to further investigate the local structure of the coastal current for the late winter season, March-April.

The circulation is simulated with a state-of-the-art prognostic Finite Element model incorporating heat and salt transport and turbulence closure in tidal time. The computational domain includes the regional area associated with the coastal current. The essential Gulf-wide influence is incorporated through boundary conditions obtained from a Gulf-scale simulation.

Prognostic simulations with climatological mean forcing are examined along two cross-shore transects near critical estuaries. The simulations show significant sharpening of the frontal structure relative to the observed climatological salinity structure, and the diagnostic flow fields derived therefrom. The prognostic physics is largely responsible for this effect; the inclusion of riverine sources in the present calculation is also important on the shoreward side of the MCC.

A simulation involving observed winds demonstrates the variability induced by time-and space-varying wind forcing. The event shows significant local response in terms of upwelling, offshore spreading of the coastal current, and alongshore flow reversal relative to the climatological mean.

Introduction
The Gulf of Maine is a semi-enclosed coastal sea bounded by New England on the west and north, by New Brunswick and Nova Scotia on the east and north, and by Georges Bank at the shelfbreak (Figure 1). The coastal current is the shoreward manifestation of the large-scale cyclonic circulation in the Gulf, depicted in Figure 2. The Gulf-wide cyclonic circulation is caused by: a) barotropic throughflow from the Scotian shelf entering at Southwest Nova Scotia and following the terrain around the Gulf; and b) seasonal intrusion of dense slope water through the Northeast Channel and spilling into the deep basins (Brooks 1985; Brown and Irish 1992, 1993). These physical influences set in place the basic coastal current and its seasonal modulation, and are dominant seaward of
roughly the 100 m isobath. Inshore of this point, the dynamics shift to local influences, including locally-variable winds, the along-coast frontal structure, and buoyancy inputs from freshwater runoff at the coast (Lynch et al., 1995b).

![Gulf of Maine Map](image)

Figure 1: Gulf of Maine Map

The transport pathways in the coastal current are of intrinsic interest. Toxic phytoplankton blooms, nutrients, and pollutants are all transported via the coastal current (Franks and Anderson 1992a,b, Brooks and Townsend 1989). It is therefore essential for environmental managers, and other scientists concerned with the ecosystem in the Gulf of Maine, to understand how the coastal current responds to variable forcing.

In a previous study (Lynch et al. 1995b) we established a basic computational framework for the exploration of these matters, using both a Gulf-scale simulation to establish the underlying basin-scale dynamics, and a smaller-scale and more highly resolved simulation to explore the local interactions. Herein we continue this study and examine the effects of local buoyancy sources and space and time-variable winds. Both are key contributors to variability in the coastal current, and as one moves shoreward, the variability becomes more important than the mean in certain contexts.
Figure 2: Gulf-scale Prognostic Streamfunction Response for March-April, the contours are in increments of 0.1Sv.

**Prognostic Time-Domain Model**

We employ a state-of-the-art finite-element circulation model, described in detail in Lynch et al. [1995a,b]. The model is three-dimensional with a free surface, partially mixed vertically, and fully nonlinear. It transports momentum, heat, salt, and two turbulent variables in tidal time. Both barotropic and baroclinic motions are resolved in tidal time.

Vertical mixing is represented by a level 2.5 turbulence closure scheme [Mellor and Yamada, 1982; Galperin et al., 1988; Blumberg et al. 1992]. Horizontal mixing is represented by a mesh- and shear-dependent eddy viscosity similar to Smagorinsky (1963).

Variable horizontal resolution is achieved with unstructured meshes of conventional linear triangles. In the vertical, a general terrain-following coordinate system is used, with a flexible, nonuniform vertical discretization. This allows continuous vertical tracking of the free surface and proper resolution of surface and bottom boundary layers.
Source terms allow fluid and buoyancy discharges at all points in the 3-D space.

Figure 3: CSTB.1A Mesh. There are 3618 nodes and 6618 elements. The circles represent the river source input locations. SJ - St. John, SC - St. Croix, P - Penobscot, KA - Kennebec and Androscoggin, S - Saco, and M - Merrimack. The lines represent the transects displayed in the results.

Procedure
The procedure for the calculations presented here is as discussed in Lynch et al [1995b]. The important points are that: a) a Gulf-scale climatological prognostic simulation, as in figure 2, produced the initial and boundary conditions for the coastal mesh (figure 3); b) climatological values for heat flux were used at the surface on the coastal mesh; c) river sources are turned on using a decadal (1980's) bi-monthly average for source strength; d) time- and space- variable winds are used and contrasted to the climatological wind response. Tidally averaged circulation and salinity fields are displayed, after an adjustment period of nine days.

Three different cases will be shown: 1) March-April without river sources; 2) March-April with river sources; and 3) March-April with river sources under observed wind stress. Cases 1) and 2) employ climatological mean wind which is constant in space and time; case 3) uses objectively analyzed wind fields which are estimated from observations and vary spatially and temporally. In all cases, river sources are held constant at their decadal mean values.

Results
The results shown will consist of transects cut vertically through the coastal current. Two river outflow regions have been chosen: the Kennebec and An-
droscoggin (left panels), and the Merrimack (right panels). These two transects start close to their source location, noted on figure 3. The figures shown in this section have thick and thin contours; the thick contours are labeled and the thinner contours are halfway between the neighboring thick ones. The range of contours are the same for all the figures shown; isohalines go from 30.0 to 32.5 (thick increment is 0.5) and the normal velocity contours go from -0.3m/s to 0.2m/s (thick increment is 0.1). The vertical scale of the transects is in meters and the horizontal scale in kilometers. The representative transects on figure 3 are on the order of 140km in length and in the following figures only 60km is shown starting nearshore.

Figure 4: Climatological Isohalines. Kennebec and Androscoggin left; Merrimack right.

Figure 5: Diagnostic Normal Velocity(m/s). The direction convention is positive into the page(coast on the left) and negative out of the page(coast on the right).
As a point of reference, we first display in figure 4 the observed climatological salinity derived from the extensive AFAP observational data base (Loder et al, 1995) which was used to initialize the Gulf-scale simulations. Accompanying this in figure 5 is a diagnostic model solution derived from that data in a Gulf-scale calculation by Naimie et al [1994]. On both transects the presence of a coastal current is apparent in both the freshwater signature and the along-shore current structure.

![Figure 6: Isohalines: Prognostic Model, no sources](image6)

![Figure 7: Normal Velocity(m/s): Prognostic Model, no sources](image7)

Next we examine the prognostic response to climatological (March-April) forcing. The first simulation (figures 6, 7) is done without river sources, although the initial conditions contain their climatological buoyancy signatures. Relative to figure 4, the isoalines are distinctly more vertical. The density-transporting simulation shows an increase in transport in the Merrimack transect and a more
localized coastal current with a larger maximum normal speed in the Kennebec and Androscoggin transect. It is reasonable to conclude that the observed buoyancy signature in figure 4 is spread horizontally by the climatological averaging; that the diagnostic calculation based on it is therefore compromised in its local details; and that these are partly reinstated by incorporation of more realistic physics – buoyancy transport and advanced turbulence closure.

![Figure 8: Isohalines: Prognostic Model, sources active](image1)

![Figure 9: Normal Velocity(m/s): Prognostic Model, sources active](image2)

**No Source vs. Source**

The same simulation, but with river sources activated, is shown in figures 8 and 9. The impact of the freshwater influx is dramatic in the nearshore salinity, and relatively unimportant further off-shore. It is immediately apparent in figure 9 that the coastal current has increased in strength, shifted closer to shore, and is accompanied by additional counterflow at depth. On the Merrimack transect,
the normal speed at the surface is almost doubled by the river influence. Further
off-shore, little difference is noted relative to the no-source simulation, which
corresponds well with the salinity fields. The relatively small change offshore
signifies that the coastal current is strongly linked to the Gulf-scale circulation,
represented here by the boundary conditions.

**Climatological vs Observed Wind**

Finally, an experiment with observational winds was performed. The hourly
wind fields are taken from seven NOAA buoys stationed within the Gulf of
Maine. The stations were objectively analyzed onto a Gulf-scale model domain
by Feng and Brown (1996). The time period March 6, 1986 through March 8,
1986 was used; it contains a strong southwestward wind which reverses halfway
through the period, becoming a northeastward wind. Peak wind stress in both
parts of the event is of order 1 Pa, roughly 20 times the climatological mean.
A spin up time of 13 hours was used to go from the climatological wind as an
initial condition to the first observational wind. To observe the effect of the
time- and space-variable winds a moving tidal average was calculated 16 times
per M2 period.

The wind was originally run on the Gulf-scale domain. The results of the
southwestward wind, not included here, showed an increase in the cyclonic cir-
culation in the Gulf by a factor of two. The pressure response along the coast
increased approximately 5-8 cm. In the deep basins of the Gulf the response was
much smaller: negligible response could be seen in the East, while the Western
response was on the order of a couple of centimeters. This simulation demon-
strated that modeling on the coastal mesh using only the climatological pressure
response on the open boundary would not seriously contaminate the results
nearshore.

The observational winds on the coastal domain mesh were applied with river
sources active at climatological values. In the next figures to be shown the same
transects as shown before will be used. Figures 10 and 11 show the results
during the southwestward part of the wind event; figures 12 and 13 show the
later results during the northeastward wind event.

**Southwestward Wind**

*Kennebec and Androscoggin transect:* Under the southwestward wind (figure
11) the coastal current has increased approximately 0.1 m/sec from the climato-
logical simulation with river sources included (figure 9). The flow is apparently
dominated by the wind with little or no counterflow along the shelf. However,
nearshore counterflow exists; it is caused by the perpendicular intersection of the
wind to the bay walls. This produces downwelling on the downwind side and
upwelling on the upwind side of the bay. The isohalines have mixed vertically,
related to downwelling from the northeastward Ekman transport, and only curve
into the bottom to satisfy the no flux condition there (figure 10). It is interesting
to note that the wind is apparently trapping the river outflow near the coast.
The maximum normal velocity of the current is found in the same location as
the most severe baroclinic gradient.

*Merrimack transect:* This transect does not perpendicularly cut the coastal current or the wind. Therefore these results, which are related to the Ekman transport to the northeast, show little change in the isohalines of figure 10. In figure 11 complicated flows result due to the orientation of the transect and the complex topography. The coastal current must navigate Jeffrey’s Ledge and Cape Ann. The coastal current maxima nearshore in figure 9 has been submersed in figure 11. The northeastward Ekman transport at the surface causes a southwestward counterflow at depth. Therefore in figure 11 the southward component of this counterflow appears as a jet over Jeffrey’s Ledge and shifts the maximum normal velocity of the coastal current deeper.

![Figure 10: Isohalines: Southwestward wind event](image1.png)

![Figure 11: Normal Velocity(m/s): Southwestward wind event](image2.png)
Northeastward Wind

Kennebec and Androscoggin transect: Under the northeasterly wind the coastal current has shifted direction quite markedly (figure 13). However, to the off-shore side of the transect, just below the surface there is a westward current present. This feature is observed throughout the wind simulation; it is the Gulf-scale signature of the coastal current, which decreases in size and moves offshore while the nearshore wind response takes effect. The isohaline structure shows a vertically more stratified result caused by the Ekman transport of coastal buoyancy off-shore (figure 12). There is evidence of upwelling along the bottom in figure 12. It is interesting to compare this result with the climatological mean salinity structure, which is averaged over such events.

Figure 12: Isohalines: Northeastward wind event

Figure 13: Normal Velocity (m/s): Northeastward wind event

Merrimack transect: The southwestward Ekman transport under the north-
eastward wind in figure 13, depicts two near-surface currents and a strong counterflow nearshore and at depth. As in the southwestward case, this transect again shows complicated results. The normal velocity (figure 13) depicts the surface effect of the wind by moving the near-surface currents offshore relative to figure 9. The at depth northeastward counterflow results in the northward component to appear over Jeffrey's Ledge, the opposite of the southwestward wind. The isohalines (figure 12) show dramatic transport offshore and upwelling near the bottom indicative of this wind event.

Conclusion

The Maine Coastal Current location, intensity, and contents are greatly impacted by river sources and wind events. However, none of these simulations would be realistic without the inclusion of the Gulf-scale response which forms the dynamical baseline. The river sources greatly influence the local buoyancy structure. The coastal current maxima generally occurs where the density contrast is greatest. The wind event greatly changed the climatological fields by mixing and shifting direction of the nearshore currents and effectively moving the coastal current offshore under northeastward conditions. Under southwestward conditions the opposite occurs, with the coastal current intensifying as it is crowded against the topography. The Ekman transport of salinity shoreward is inhibited by the river sources causing little or no change, while seaward transport shows significant motion of the isohalines. It is apparent that the combination of the baroclinic structure and wind direction can cause significant variability of the coastal current.

This is a first step towards understanding and incorporating observational winds. In the future more investigation into the wind variability and effect on the location of the coastal current and its offshore dispersal will be completed. This will include further tests of the open boundary conditions to account for the Gulf-scale wind response, and more scrutiny of the nearshore details of estuarine discharge, which appear significant.

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References


